

UNDERSTANDING NEW ELEMENTS OF ACCELERATION AND TRANSPORT OF SOLAR ENERGETIC PARTICLES (SEPs) FROM THE SUN TO THE EARTH

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Final Report

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14. ABSTRACT This report summarizes the research results of this task which were published in four refereed journal articles. The three basic topics are: (1) Elemental abundances of solar energetic particles (SEPs) in various solar wind streams (Kahler et al., 2009; Reames et al., 2009); (2) Elemental abundances of ground-level events (GLEs) and their variations with solar burst parameters (Kahler et al., 2011); and (3) an interpretation of the Kiplinger Effect (Kahler, 2012).								
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Table of Contents

1. SUMMARY	1
2. INTRODUCTION.....	1
3. METHODS, ASSUMPTIONS, AND PROCEDURES	2
4. RESULTS AND DISCUSSION	2
4.1 SEP Elemental Abundances in Solar Wind Streams	2
4.2 ACR Elemental Abundances in Magnetic Clouds.....	3
4.3 GLE Elemental Ratios and Associated CME and Flare Characteristics	5
4.4 The Kiplinger Effect	6
5. CONCLUSIONS	9
REFERENCES.....	10

List of Figures

1. Schematic Diagram of SEP Gyrating on Solar Wind Spiral Field Line from Shock to Earth ...	4
2. Plot of Abundance Ratios for Each of Three Solar Wind Types	4
3. Magnetic Cloud Field Configuration and ACR Intensities.....	5
4. Electron/Proton Ratios Versus X-Ray Flare Rise Times	6
5. Normalized Event Fe/O Ratios Versus the Flare Longitudinal Separations.....	6
6. RHESSI Dynamic Plots of the 2003 May 29 SHH Hard X-ray Burst.....	8

List of Tables

1. Contingency Table for Studies of All SEP Events	7
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1. SUMMARY

This report discusses four studies on observations of solar and galactic energetic particles carried out under the aegis of a task funded by the Air Force Office of Scientific Research. We found that the elemental composition of solar energetic particles (SEPs) in fast solar wind streams does not vary from that in slow wind streams. Two results providing evidence against the common interpretation that solar flares are major contributors to SEP events were (1) that the elemental composition of SEPs in ground-level-events (GLEs) does not systematically vary with solar source longitude of the SEP events; and (2) that signatures of shock acceleration provide associations with SEP events as good as the soft-hard-hard X-ray signatures of solar flares. Finally, we used anomalous galactic cosmic rays to probe the magnetic topology of interplanetary magnetic clouds and found evidence for open topologies.

2. INTRODUCTION

It has been known for more than six decades that the Sun produces transient bursts of solar energetic particle (SEP) events that can have deleterious consequences for human activities. These events consist of protons and ions with energies typically extending to tens of millions of electron volts (MeV), sufficient to produce enhanced electron densities in the ionosphere. Several times per solar cycle the event energies extend to giga-electron volts (GeV), which can be measured by ground-based detectors. The typical SEP events are detected by satellites and envelope the Earth for periods of several hours to several days.

The characteristics of SEP events such as their peak intensities, spectra, and elemental and isotopic compositions have been extensively measured. We now understand that there are two classes of SEP events (Reames 1999): (1) the impulsive events, defined by low intensities, limited spatial extent, and enhanced heavy element abundances; and (2) the gradual events, defined by high intensities, large spatial extent in interplanetary space, and elemental abundances comparable to those of the solar corona. The first group is associated with small solar flares and the second with coronal shocks driven by fast coronal mass ejections (CMEs). The favored paradigm is that impulsive particle events are produced in short (~ 10 min) episodes of local magnetic reconnection in solar active region flares, and the gradual events originate in prolonged (\sim hours) particle acceleration by broad shock waves driven by fast and wide CMEs. The gradual events that are important for space weather effects are the focus of our interest.

Within this basic picture of SEP events lie many bewildering problems. Perhaps the most challenging problem is to understand which solar energetic events will produce SEP events at Earth and what the characteristics of the resulting events will be. There is a rough correlation of the peak 20 MeV SEP intensities with the speeds of associated CMEs, but for any given CME speed the resulting observed SEP events have a range of 4 to 5 decades of peak intensities. The problem is to understand what other coronal or interplanetary characteristics play roles in SEP production. We also know that solar flares produce SEPs that can be observed on the Sun by the radiation they produce in collisions with the ambient corona and chromosphere. Are those SEP populations related to the populations observed at 1 AU, and if so, how?

The three-year basic research effort funded by the Air Force Office of Scientific Research (AFOSR) and summarized in this Final Report was aimed at improving our understanding of the

origins and characteristics of SEP events by attacking several specific problems ready for fruitful analyses. The proposed work, with the ultimate goal of reliable prediction and effects mitigation, had two focused objectives: (1) understanding the solar origins of SEP events and; (2) looking for SEP event dependences on solar wind structures. Our work led to three published papers in the refereed literature in these areas and a fourth paper on a topic that arose somewhat serendipitously regarding energetic particle propagation inside magnetic structures presumed to be topologically closed. In the next section, we summarize and excerpt the results reported in detail in each of these four papers.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

We use observational data taken from several NASA spacecraft experiments to test our understanding of the origin of SEPs. In particular we use the electron to proton (e/p) and iron to oxygen (Fe/O) ratios as functions of various SEP and solar signatures to look for possible flare signatures of SEPs. The solar data are taken from ground and space-based observatories, including solar hard X-rays from the NASA RHESSI satellite.

4. RESULTS AND DISCUSSION

4.1 SEP Elemental Abundances in Solar Wind Streams

The solar energetic ($E > 1$ MeV/nucleon) particles (SEPs) observed in gradual events at 1 AU are assumed to be accelerated by coronal/interplanetary shocks from ambient thermal or suprathermal seed particles. If so, then the elemental abundances of SEPs produced in different solar wind (SW) stream types (transient, fast, and slow) might be systematically distinguished from each other. SEPs accelerated at a point where a CME-driven shock crosses a SW stream region will be essentially confined to that stream region as they gyrate along the interplanetary spiral field of the wind stream (Figure 1) to the Earth. Do the expected SW stream dependences of elemental abundances appear in the SEP observations or not?

We looked for these differences in SEP energy spectra and in elemental abundance ratios (including Mg/Ne and Fe/C, which compare low/high first-ionization potential (FIP) elements) in a large number of SEP time intervals over the past solar cycle. The SW regions were characterized by the updated three-component stream classification of Richardson et al. (2002). Our survey, published in Kahler et al. (2009), showed no significant compositional or energy spectral differences in the 5-10 MeV/nucleon range for SEP events of different SW stream types. Figure 2 shows the SEP elemental ratios of Fe/C, Mg/Ne, and C/O for the three stream types of 1 = ICME, 2 = fast wind, and 3 = slow wind. A similar grouping of power-law spectral indices for 3-10 MeV/nuc He, C, O, and Fe show differentiation by solar wind stream type. These results extended the earlier finding that SEP events are observed frequently in fast SW streams (Kahler, 2004, 2005) even though their higher Alfvén and SW flow speeds should constrain SEP production by CME-driven shocks in those regions.

4.2 ACR Elemental Abundances in Magnetic Clouds

In carrying out the previous work on elemental SEP abundances in SW streams, the abundances of energetic particles in ICMEs were calculated. A particular kind of ICME is the magnetic cloud (MC), defined by its enhanced magnetic field intensity and smooth rotation in space. This is thought to be indicative of a twisted magnetic flux rope convected past the spacecraft. The MC fields are thought to be topologically closed or open, based on the presence of bidirectional or unidirectional solar wind electron heat fluxes, respectively. If the fields are closed, we expect that charged particles originating outside the MC will be excluded from those regions of the MC. The anomalous cosmic rays (ACRs) originate at or near the heliospheric termination shock and propagate inward along open magnetic field lines (Fisk et al., 1974) to 1 AU. If the MC field lines are closed, the ACRs should be absent from those regions because of their small gyroradii and small cross-field diffusion path lengths.

The few-MeV/nuc ACRs are distinguished by their elemental composition from the SEPs. It is therefore possible to observe the intensity variations of ACRs through various MCs. Using a list of MCs previously generated by Shodhan et al. (2000), we examined the ACR intensities inside and outside MCs with particle data from the EPACT instrument on the Wind spacecraft. The surprising result was that no variation in the ACR intensities was observed through any of the MCs, independently of whether the fields were open or closed. Figure 3 shows an example of the MC number 5 of the Shodhan et al. (2000) list. The top panel shows the magnetic field phi and theta components with the familiar pattern of smooth rotation characteristic of MCs. The bottom panel shows the intensities of three ACR elements, He, O, and C, with two energy ranges for O.

The ACRs serve as probes of the large scale MC structures through which the SEPs must also propagate in many of the SEP events observed at 1 AU. The ACR results are not consistent with the expected decreases of energetic charged particles in closed fields of MCs (Richardson and Cane, 2011). The results are at least consistent with appearance of SEPs inside MCs, although with perhaps somewhat shorter event time scales (Kahler, 2005).

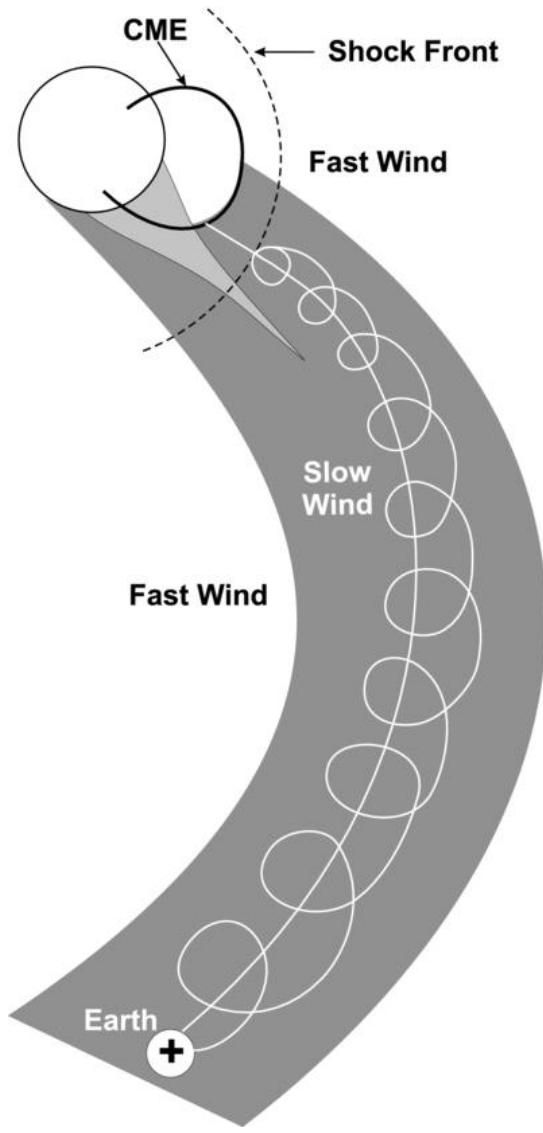


Figure 1: Schematic Diagram of SEP Gyrating on Solar Wind Spiral Field Line from Shock to Earth

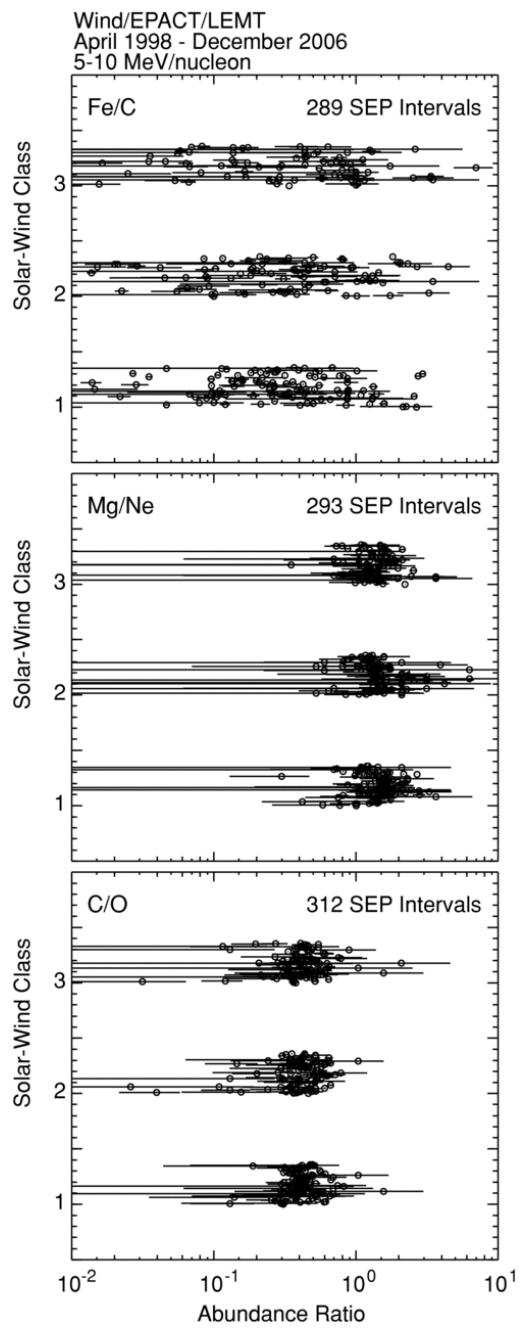


Figure 2: Plot of Abundance Ratios for Each of Three Solar Wind Types

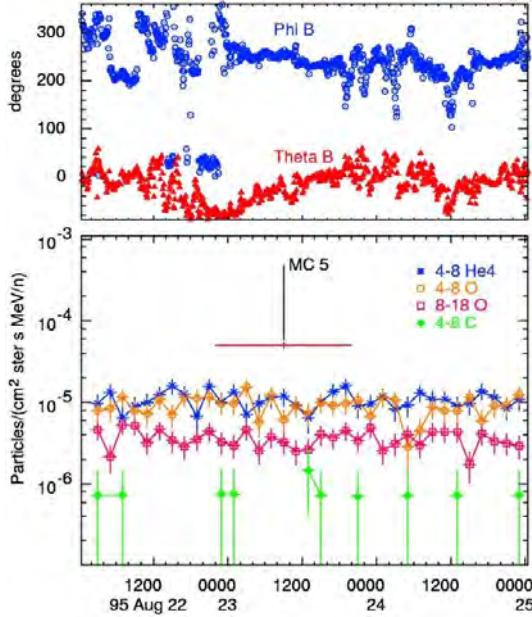


Figure 3: Magnetic Cloud Field Configuration and ACR Intensities

4.3 GLE Elemental Ratios and Associated CME and Flare Characteristics

Solar energetic particle (SEP) events reaching rigidities > 1 GV are observed at 1 AU as ground-level events (GLEs). They are considered to be extreme cases of gradual SEP events, produced by shocks driven by wide and fast CMEs that are usually associated with long-duration (> 1 hour) soft X-ray (SXR) flares. However, some large gradual SEP events, including GLEs, are associated with flares of short-duration (< 1 hour) time scales comparable to those of flares seen with impulsive, low-energy SEP events with enhanced charge states, heavy-element abundances, and e/p ratios.

The association of some GLEs with short-duration SXR events (Kahler et al., 1991) challenges us to understand the GLE event-to-event variation with SXR durations and whether it truly reflects the nature of the particle acceleration processes or simply the characteristics of the solar regions from which large, fast CMEs arise. We examined statistically the associated flare, active region (AR), and CME characteristics of ~ 40 GLEs observed since 1976 to determine how the GLE e/p (electron/proton) and Fe/O (iron/oxygen) ratios, each measured in two energy ranges, depend on those characteristics in the paper of Kahler et al. (2011). The abundance ratios trended weakly to lower, more coronal, and less scattered values with increasing flare timescales, thermal and nonthermal peak fluxes, and measures of source AR sizes. Figure 4 shows the example of the logs of the low energy ($e > 1$ MeV)/($p > 430$ MeV) e/p ratios versus the logs of the SXR flare rise times measured in minutes. It is the only case of a significant correlation with SXR time scales. The best fit is shown by the diagonal line.

We also examined the elemental abundance ratios as a function of the magnetic longitudinal separation of the observed footprint from the source flare site. The result for the Fe/O high (47-

80 MeV/nuc or 50-75 MeV/nuc) parameter is shown in Figure 5. The separations are calculated using the event solar wind values. If there is a significant flare contribution to GLE events, we should expect to find a decrease in Fe/O with longitudinal separation. The wide range of solar longitude connections for GLEs with high abundance ratios combined with the previous statistical results argue against a significant role for flare effects in the GLEs. We suggest that GLE SEPs are accelerated predominately in CME-driven shocks and that a coupling of flare size and time scales with CME properties could explain the SEP abundance correlations with flare properties.

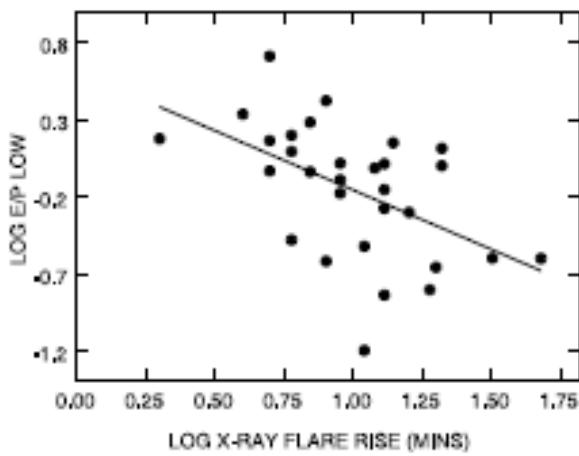


Figure 4. Electron/Proton Ratios Versus X-Ray Flare Rise Times

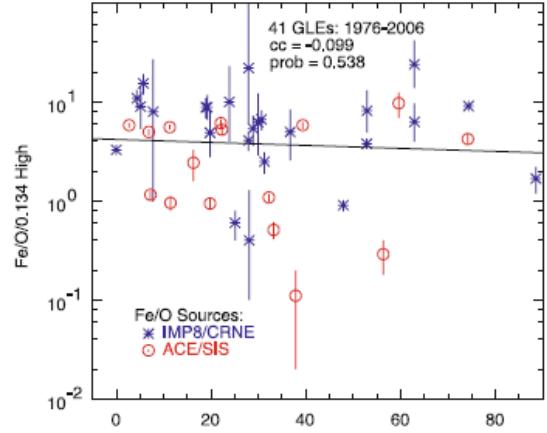


Figure 5. Normalized Event Fe/O Ratios Versus the Flare Longitudinal Separations

4.4 The Kiplinger Effect

The Kiplinger effect is an observed association of solar energetic ($E > 10$ MeV) particle (SEP) events with a “soft-hard-harder” (SHH) spectral evolution during the extended phases of the associated solar hard ($E > 30$ keV) X-ray (HXR) flares (Kiplinger, 1995). Besides its possible use as a space weather predictor of SEP events, the Kiplinger effect has been interpreted as evidence of SEP production in the flare site itself, contradicting the widely accepted view that particles of large SEP events are predominately or entirely accelerated in shocks driven by coronal mass ejections (CMEs) (Reames, 1999; Kahler, 2005; Cliver, 2009). We reviewed earlier work to develop flare soft X-ray (SXR) and HXR spectra as SEP event forecast tools and then examined recent evidence from the Ramaty High-Energy Solar Spectrometric Imager (*RHESSI*) supporting the association of SHH HXR flares with large SEP events.

We found that ad hoc prediction criteria using the CME widths and SXR flare durations of associated *RHESSI* hard X-ray bursts (HXBs) can yield results comparable to those of the SHH prediction criteria. Table 1 shows the combined contingency tables of the Kahler (2012) paper in the *Astrophysical Journal*. In each of the four labeled studies a prediction criterion is adopted for the occurrence of SEP events at the lowest intensity threshold for satellite particle experiments at

$E > 10$ MeV. The original Kiplinger statistics are compared with those of a recently published study of Grayson et al. (2009) and the ad hoc use of SXR durations and CMEs of width $> 120^\circ$. With a figure of merit $M = \text{SEP predictions}/(\text{missed predictions} + \text{false alarms})$, we get values for the flare and CME parameters equal to or exceeding those of the SHH X-ray parameters.

Table 1. Contingency Table for Studies of All SEP Events

Study	Criterion	SEP Event Observed	No SEP Event Observed
A (Kiplinger 1995)^a			
Fp > 0.1 pfu SEP	HXB SHH	18	6
	HXB no SHH	4	124
B (Grayson et al. 2009)^b			
Fp > 0.1 pfu SEP	HXB SHH	13	5
	HXB no SHH	1	18
C (This study)^c			
Fp > 0.1 pfu SEP	GOES D > 25 minutes	11	2
	GOES D < 25 minutes	3	21
D (This study)^d			
Fp > 0.1 pfu SEP	CME W $> 120^\circ$	13	2
	CME W $\leq 120^\circ$	0	14

Notes.

^a All HXRBS/*SMM* HXBs with ≥ 5000 photons s^{-1} and all Fp > 0.1 pfu SEP events associated with those HXBs.

^b 37 *RHESSI* well-connected ($W30^\circ$ – $W90^\circ$) full-coverage HXBs with SHH evolution at any timescale and associated SEP events ≥ 0.1 pfu. See the text for two changes from the original Table 2 of Grayson et al. (2009).

^c 37 associated *GOES* SXRs from Table 2 of Grayson et al. (2009). Criterion for SEP event is *GOES* duration D > 25 minutes.

^d 29 associated LASCO CMEs from Table 2 of Grayson et al. (2009). Criterion for SEP event is CME W $> 120^\circ$.

An examination of the *RHESSI* dynamic plots also revealed several ambiguities in the determination of whether and when the SHH criteria are fulfilled, which must be quantified and applied consistently before an SHH-based predictive tool can be made. Two of the characteristics can be seen in the dynamic plot of Figure 6. The 2003 May 29 plot shows from top to bottom: a color-coded dynamic energy spectrum; the 40–70 keV flux plot; and the spectral index γ over the time interval. We see first, a succession of impulsive hard X-ray bursts, each with a SHS behavior, occur in sequence from 0101–0105 UT, each more intense than the previous burst. Since the X-ray burst spectra are harder with increasing intensity, the spectral index of the sequence takes on a SHH behavior, which it might not do if only a single burst occurred.

Second, after 0107 UT, the apparent hardening of the spectrum occurs, but only because the fluxes are declining toward a background with an intrinsically harder spectrum. Finally, not shown here, the SHH behavior can be energy dependent, apparent in one spectral region, but not in another. These effects all need clarification if HXR spectral behavior is to be employed as a space weather tool.

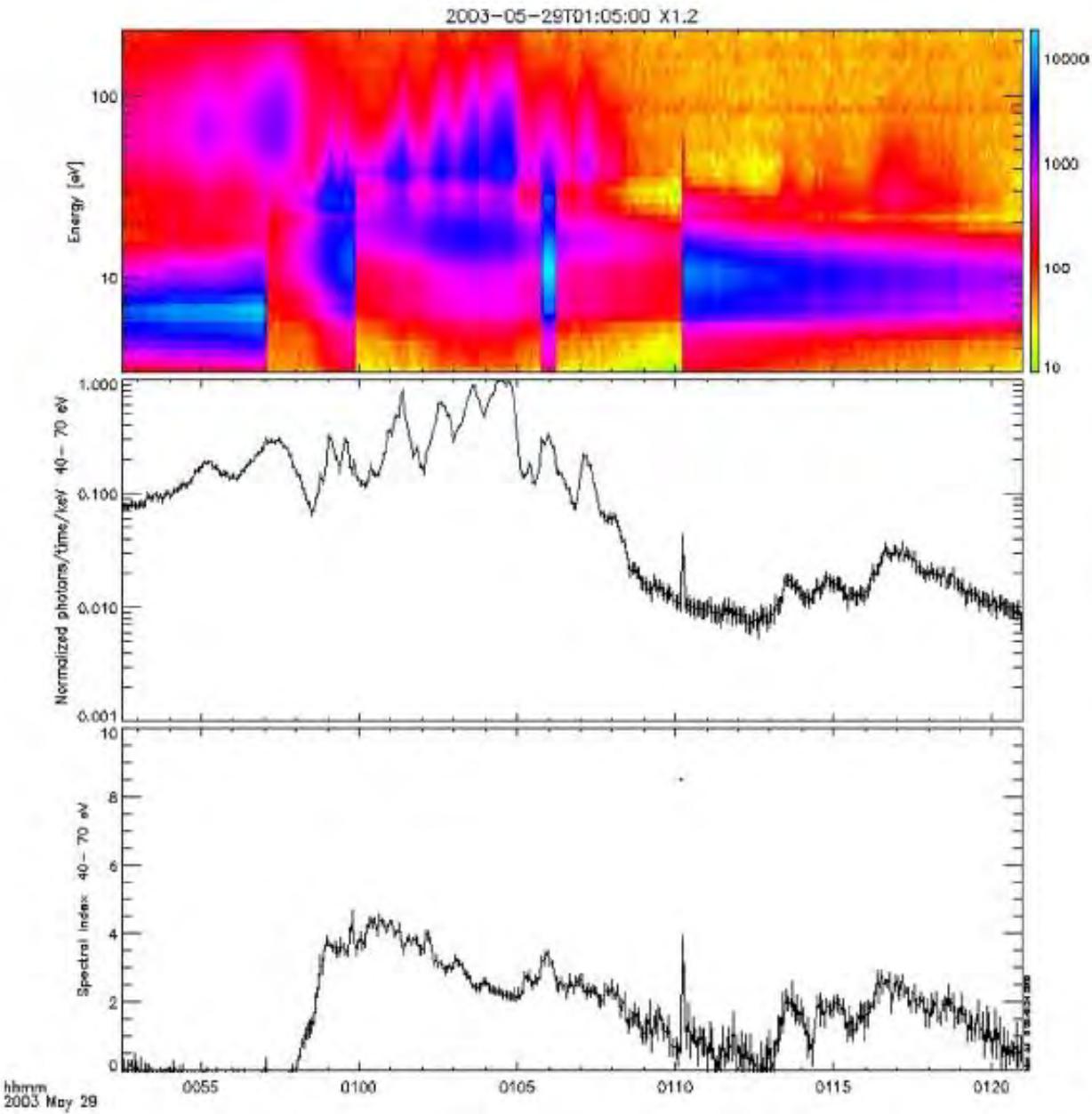


Figure 6. RHESSI Dynamic Plots of the 2003 May 29 SHH Hard X-ray Burst

A comparative HXR spectral study beginning with the large population of relatively smaller SEP events has yet to be done, and we argued that those events will not be so well predicted by the SHH criteria. SHH HXR flares and CMEs are both components of large eruptive flare events,

which accounts for the good connection of the SHH HXR flares with SEP events. Thus, the Kiplinger effect is consistent with the general paradigm of SEP acceleration at CME-driven shocks.

5. CONCLUSIONS

The work described in the previous section centers on the basic paradigm of SEP production by CME-driven shocks. On the one hand, there have been challenges to the paradigm, with the suggestion that accompanying solar flares are the primary or at least an important source of SEPs. Work on the Kiplinger effect and the properties of GLEs cited here has shown that, contrary to claims by various authors, properties of gradual $E > 10$ MeV SEP events are consistent with the simple shock paradigm and do not call for a flare SEP component.

Looking for evidence of intensity or time variations in SEP events due to large scale SW structures, on the other hand, has so far not been fruitful. We have found no indication that the presence of fast or slow wind streams or transient ICME features in space has any detectable effects on the SEP characteristics. This may indicate that shocks and shock acceleration are robust features of CMEs that transcend the characteristics of the coronal or interplanetary media through which they propagate. We continue to probe for relationships of environmental effects on SEP production and propagation because the variations in SEP event intensities and time scales range over orders of magnitude that have yet to be well organized by environmental signatures. Figures 2 and 5 illustrate the large dynamic ranges of elemental ratios that are not organized by solar wind stream type or solar longitude, respectively. We expect that some organizing parameter(s) should exist, and that they will be of value in the forecasting of SEP events. Our work continues in the renewal to this AFOSR grant.

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